

The “Kinetic Stabilizer”: A Simpler Tandem Mirror Configuration?

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THE "KINETIC STABILIZER": A SIMPLER TANDEM MIRROR CONFIGURATION?

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ABSTRACT

In the search for better approaches to magnetic fusion it is important to keep in mind the lessons learned in the 50 years that fusion plasma confinement has been studied. One of the lessons learned is that "closed" and "open" fusion devices differ fundamentally with respect to an important property of their confinement, as follows: Without known exception closed systems such as the tokamak, the stellarator, or the reversed-field pinch, have been found to have their confinement times limited by non-classical, i.e., turbulence-related, processes, leading to the requirement that such systems must be scaled-up in dimensions to sizes much larger than would be the case in the absence of turbulence. By contrast, from the earliest days of fusion research, it has been demonstrated that open magnetic systems of the mirror variety can achieve confinement times close to that associated with classical, i.e., collisional, processes. While these good results have been obtained in both axially symmetric fields and in non-axisymmetric fields, the clearest cases have been those in which the confining fields are solenoidal and axially symmetric. These observations, i.e., of confinement not enhanced by turbulence, can be traced theoretically to such factors as the absence of parallel currents in the plasma, and to the constraints on particle drifts imposed by the adiabatic invariants governing particle confinement in axisymmetric open systems. In the past the MHD instability of axially symmetric open systems has been seen as a barrier to their use. However, theory predicts MHD-stable confinement is achievable if sufficient plasma is present in the "good curvature" regions outside the mirrors. This theory has been confirmed by experiments on the Gas Dynamic Trap mirror-based experiment at Novosibirsk. In this paper a new way of exploiting this stabilizing principle, involving creating a localized "stabilizer plasma" outside a mirror, will be discussed. To create this plasma ion beams are injected along the field lines in such a way as to be reflected before they reach the mirrors, thus forming a localized peak in the plasma density. It will be shown that the power required to produce these stabilizing plasmas is much less than the power per meter of fusion power systems that might employ this technique. Use of the Kinetic Stabilizer idea may therefore permit the construction of tandem mirror fusion power systems that

are much smaller and simpler than those based on the use of non-axisymmetric fields to achieve MHD stability.

1) INTRODUCTION

The 50-year-long history of research into the confinement of plasma in magnetic fields should have taught us one clear lesson: There is a fundamental difference in the character of plasma confinement between that in so-called "closed" systems, such as the tokamak, the stellarator or the reversed-field pinch, and "open" systems, such as those based on the use of the magnetic mirror principle to provide axial confinement. Closed systems, with no known exceptions, show confinement that is dominated by turbulence-related processes, rather than by "classical," i.e., collision-related, processes. As a result, to achieve confinement adequate for fusion power purposes in, for example, the tokamak requires that it be scaled up in size and power level to the point that its ultimate practicality as an economically viable source of fusion power is open to question. By contrast, from earliest days there have been examples of open systems where turbulence, if present at all, is at such a low level that only collision-related processes play a significant role in determining the confinement.

Given the above-described historical record in magnetic fusion research, and given the growing impetus to look for "simpler, smaller" approaches to fusion power than the present main-line approaches, open systems would seem to be the most fertile area for such a search. However, from the beginning, the issue of the end losses from mirror-based systems has been seen as a major barrier to their employment for fusion power purposes. The invention of the tandem mirror in the 1970's provided an answer to this particular objection, and opened a new era in mirror research. However, despite the major successes achieved in plugging the end leakage of mirror systems by the potential barriers generated in tandem-mirror systems, another issue has limited progress in these systems. This issue is the one associated with the use of non-axisymmetric fields in the central cell and/or the end cells of such systems.

Following the first demonstration of the magnetic well as a stabilizing means in the famous Ioffe

experiments of the 1960's, the stabilization of the latent MHD instability of mirror-based systems by non-axisymmetric "magnetic well" fields has been a central feature of research on open-ended systems. However, the use of such fields compromises the essential simplicity of the potential confinement idea of the tandem mirror by introducing modes of resonance-enhanced radial transport that are associated with the particle drifts in non-axisymmetric magnetic fields. Elimination of the need for magnetic-well-type fields and a return to the use of axisymmetric fields would remove this last objection to the tandem-mirror approach, and could therefore lead to a renaissance in mirror research.

Since the earliest days of research on open-ended magnetic fusion systems the potential advantages of employing axially symmetric confining fields have been understood. In early experiments using axisymmetric fields, for example in the Table Top [1] experiments in 1960 at Livermore, very low cross-field transport was found, more than five orders of magnitude smaller than the Bohm rate. Nevertheless, as has been noted, most open-ended systems early on adopted non-axisymmetric magnetic wells to achieve MHD stability. The price: increased complexity and greater cross-field transport. Recently, however, in the Gas Dynamic Trap [2] at Novosibirsk, axially symmetric mirror fields have again been used, with MHD stabilization being provided by a new means. In those experiments, as shown theoretically by Ryutov [3], the high density of the confined plasma results in an outflowing plasma whose density is high enough in the "good" curvature region of the magnetic field outside the mirrors to stabilize the confined plasma at beta values of order 30 percent.

In an earlier paper [4] a "Kinetic Tandem" concept has been described in which the "plugs" of a tandem mirror are formed by aiming ion beams up the magnetic gradient at the ends of a simple solenoidal field. At the reflection point of the ions the plasma density builds up to produce a peaked plasma density profile as in the plugs of the original tandem mirror idea. However, because of the high beam-power needed for the plugs, in order to yield net fusion power in the Kinetic Tandem kilometers-long confined plasmas are required.

The "Kinetic Stabilizer" idea marries the stabilization technique demonstrated in the Gas Dynamic Trap with the plasma density peak of the Kinetic Tandem. In this way one can MHD-stabilize a tandem mirror system that uses only axially symmetric mirror cells. Here the beam-produced plasma density peak would be located outside the last mirror field, at an optimized location on the expanding field lines between the mirror and the physical end of the system. An important quantitative difference between the Kinetic Tandem and a tandem mirror system employing the Kinetic Stabilizer idea to insure MHD stability is that the

beam power required in the latter case is orders of magnitude smaller than that required in the Kinetic Tandem. This fact opens the door to the possibility of mirror-based fusion power systems that are far simpler and much smaller than either the present versions of the tandem mirror or systems based on the Kinetic Tandem concept.

As will be described in later sections, a code has been written that calculates the beam-produced plasma density peak and then performs the MHD stability integrals to evaluate its stabilizing effect. In an example calculation it was found that a ion-beam power of order 200 kilowatts was sufficient to MHD-stabilize a plasma column producing of order 2 megawatts per meter of plasma length. Not only is this result favorable in terms of providing a simple and energy-efficient way of stabilizing tandem mirror systems employing axially symmetric fields, but it also may make feasible a return to the original tandem mirror concept, that is, one where the potential plugging arises solely from the peaking of plasma density in the end cells, and complexities such as thermal barriers and auxiliary end cells are not required. If proved to be feasible, this type of tandem mirror system could represent an almost ideal fusion reactor from the standpoint both of simplicity and freedom from enhanced cross-field transport.

In addition to the reasons for the use of axially symmetric fields based on their superior confinement physics, there is another, engineering-related, reason for employing such fields in fusion power systems. This reason has to do with the mechanical and electrical properties of the coils used to produce the confining fields. Both long and short solenoidal coils of circular cross-section are well suited for the generation of high magnetic fields with a minimum of difficulty and cost. The stress distribution in such coils is symmetric and is therefore much easier to deal with than is the case with coils of non-circular cross-section. With circular coils it is also possible to employ "hybrid" coils, consisting of both superconducting windings and conventional conductors, to push the field levels above those achievable using superconducting coils alone. These possibilities should greatly expand the parameter space of fusion power system design, while at the same time reducing the cost of generating the confining fields. They also augur well for the possibility of returning to the original tandem mirror concept in examining new fusion power system options.

II) MHD STABILIZATION OF MIRROR SYSTEMS BY PLASMA EXTERNAL TO THE MIRRORS

The theory of the stabilization of MHD interchange instability modes in axially symmetric mirror systems by plasma present on the external, fringing, field outside the mirrors has been discussed, as noted above,

by Ryutov [3] A brief review of the plasma physics principles leading up to this concept is in order:

In axisymmetric mirror-based systems where the length of the confining field is large compared to the average ion-orbit radius, the “finite-orbit” stabilizing effect [5] operates to stabilize all but the lowest-order, $m = 1$, MHD interchange mode, a mode corresponding to a simple transverse drift of the plasma column. This lowest order mode is also a weakly driven one, in that it arises as the result of a small difference between two competing effects, namely, the stabilizing effects of particle drifts in the “good” (positive field-line curvature) regions of the field (near the mirrors) and the destabilizing drifts in the “bad” (negative curvature) regions) that lie farther in along the field lines. From a quantitative standpoint, what is required for stability is that the pressure-weighted magnet-gradient-induced drifts of the particles in plasma located between the physical ends of the system should be dominated by good-curvature particle drifts rather than by the bad-curvature drifts.

For axisymmetric mirror systems the above condition for stability takes the form of an integral (parallel to the flux surface bounding the plasma) between the physical ends of the system (that is including field lines lying outside the mirrors on which plasma may be residing). For the case we are discussing here this integral has the following form:

$$I = \int a^3 \frac{d^2 a}{dz^2} [p_{||} + p_{\perp}] dz > 0, \text{ stable} \quad (1)$$

Here $a(m)$ is the bounding radius of the plasma, and $p_{||}$ and p_{\perp} are the parallel and perpendicular components, respectively, of the plasma pressure at the location z . Notable here is the a^3 weighting of the integral, showing that plasma located at larger radii has the largest effect on the stability, stabilizing when the curvature is positive and vice versa.

In the Gas Dynamic Trap at Novosibirsk, where the plasma density is very high, the effluent plasma is sufficiently dense that the plasma pressure outside the mirrors and at large radius in the expanding field is sufficiently high to render the interior plasma MHD stable, up to beta values of order 30 percent. In ordinary, lower-density, mirror and tandem mirror systems, where the plasma is confined for many bounce periods between the mirrors, the effluent plasma density is too low to stabilize the interior plasma. If, however, a plasma could be formed and maintained in a properly chosen region with good field-line curvature outside the mirror it could stabilize the confined plasma if the condition Equation (1) is satisfied. This perception is the basis for applying the Kinetic Stabilizer idea to the problem. It is to be implemented by finding the conditions under which ion

beams injected along the field lines can be reflected at a location outside the mirrors in a manner so as to satisfy the stability criterion, Equation 1.

III) QUANTITATIVE EVALUATION OF THE STABILIZER PLASMA PARAMETERS

The problem of obtaining quantitative requirements for the employment of the Kinetic Stabilizer concept to mirror-based systems can be divided into two categories. The first category is the evaluation of the density-peaking effect of injecting ion beams up a magnetic gradient, in this case up the field gradient outside the outermost mirror. The computational method that is to be employed here is described in the cited article, Reference 4, on the Kinetic Tandem. The second category of computation is the evaluation of the MHD stability criterion, Equation 1, first for the plasma within the confinement region, and second, for the stabilizing plasma outside the mirrors, when it is located at a region of the external field that has been chosen so as to maximize the stabilization, subject to other constraints. We consider the first category in the next section.

A) Kinetic Stabilizer Plasma Density as a Function of Magnetic Field

The computational means for determining the density peaking is the following one: First, an ion angular distribution function approximating a realistic ion-source distribution is assumed. This distribution function is then expressed in terms of the adiabatic invariants of specific energy, ϵ , and specific magnetic moment, v , and is then inserted in the integral expression determining the evolution of the ion density with the local strength of the magnetic field encountered by the ions as they move up the magnetic gradient. After this density- v - ϵ distribution is calculated it is converted into a density- v - ϵ -position distribution by a transformation of variables, using the given spatial variation of the field outside the mirrors.

The form for the ion-source angular distribution that was assumed is the following one:

$$s(\theta) = s_0 [\sin^2(\theta) - \sin^2(\theta_1)]^2 [\sin^2(\theta_2) - \sin^2(\theta)]^2 \quad (2)$$

Here $\theta_1 < \theta_2$ (rad.) are the bounding angles. A plot the ion-source angular distribution function, Equation 2, for a representative case is shown in Figure 1.

The expression for the density distribution of the injected ions as a function of the local value of the magnetic field is given by the phase-space integral:

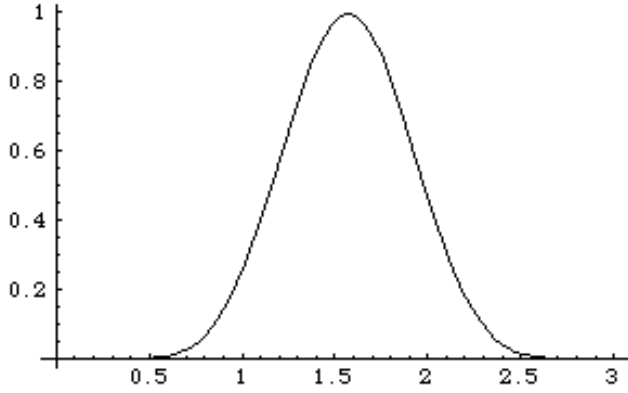


Figure 1. Example of source angular distribution (abscissa in degrees).

$$n(B) = \sqrt{2} \pi B \int_{\epsilon}^{\infty} \int_{\nu}^{\infty} g(\nu, \epsilon) (\epsilon - \nu B)^{-1/2} d\nu d\epsilon \quad (3)$$

Here $\epsilon = (1/2)\nu^2$ and $\nu = (1/2)(\nu_{\perp}^2)/B$.

For this case the distribution function, $g(\nu, \epsilon)$ is written as:

$$g(\nu, \epsilon) = f(\epsilon) s[\mu(\nu, \epsilon)],$$

$$\text{with } f(\epsilon) = \delta(\epsilon - \epsilon_0),$$

$$\text{and } \mu = \cos(\theta), \text{ so that } \mu^2 = (1 - \nu B/\epsilon)$$

If we now express the angular distribution function in terms of the invariants it takes the form:

$$s(\nu, \epsilon) = s_0 [\cos^2(\theta_1) - (1 - \nu B_0/\epsilon)]^2 [(1 - \nu B_0/\epsilon) - \cos^2(\theta_2)]^2 \quad (4)$$

The limits on the integral over the magnetic moment are given by the expressions:

$$\nu_1 = \sin^2(\theta_1)(\epsilon/B_0) \text{ and } \nu_2 = \sin^2(\theta_2)(\epsilon/B_0) \quad (5)$$

Here B_0 is the magnitude of the magnetic field at the ion sources

Given an angular distribution we may now evaluate the integral, Equation 3. For the energy distribution function in that equation we have assumed a mono-energetic beam, as is appropriate for an ion source.

The first part of the computer code that was written to calculate the parameters of the Kinetic Stabilizer performs a numerical integration of Equation 3. A plot of the results of this computation, giving the Stabilizer

plasma density as a function of the local magnetic field, is shown in Figure 2. For this case $\theta_1 = 12^\circ$ and $\theta_2 = 24^\circ$.

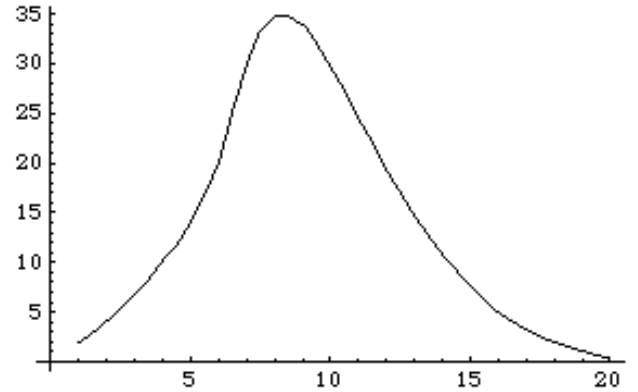


Figure 2. Calculated Kinetic Stabilizer ion density as a function of magnetic field ratio.

In the next section we will discuss the second step in the computational process, namely, the calculation of the shape of the flux surfaces in the expander upon which the Kinetic Stabilizer plasma will reside. As is evident from the form of the stability integral, Equation 1, the quantitative requirements imposed on that plasma for effective stabilization are critically dependent on the shape of the flux surfaces in the expander.

B) Flux Surface Shapes in the Expander Field

The shape of the flux surfaces in the expander region can be found by the employment of an expansion of the magnetic field in terms of its variation along the magnetic axis [6]. This expansion is:

$$B_z = B(z) - \frac{r^2}{4} B''(z) + \frac{r^4}{64} B^{(4)}(z) - \dots \quad (6)$$

$$B_r = -\frac{r}{2} B'(z) + \frac{r^3}{16} B'''(z) - \dots \quad (7)$$

As a first example of a magnetic field distribution in the expander that could be suitable for use in a Kinetic Stabilizer setting, we shall assume a Gaussian form for $B(z)$, i. e.,

$$B(z) = B_M \exp[-(z/z_0)^2] \quad (8)$$

Here B_M is the magnetic field at the mirror throat.

Given a distribution $B(z)$, the code then calculates the shape of the flux surfaces in the expander region by calculating the flux function from an integration of rB_z in radius, followed by solving for the function

$r(z)$ for chosen values of the flux. It then performs the fitting of this function with a high-order polynomial. Figure 3 is a plot of a flux surface shape for a Gaussian $B(z)$ that was obtained by this method, assuming the value $z_0 = 1.0$ m. in Equation 3. In the plot the abscissa is the axial position in meters, and the ordinate is the radius in meters. Here the initial radius (at the throat of the mirror) is .05 m., anticipating an example considered later.

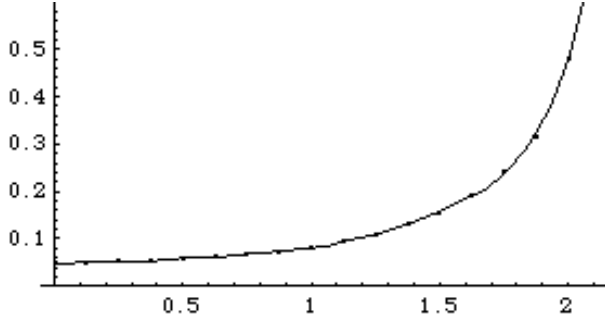


Figure 3: Gaussian flux surface, $r(z)$, showing fit by 10th (even) order polynomial.

C) Calculation of the Stabilizer Plasma Density as a Function of Axial Position

To convert the results for the density distribution as a function of magnetic field to a density distribution as a function of position in the expander region outside the mirror a paraxial assumption was made. That is, a transformation of variables was made that assumes that the field within the expander varies with axial position in the same way as the $B(z)$ that was assumed in calculating the flux surfaces. For the examples to be considered later the paraxial approximation should be a good one.

The function $n(z)$ is shown plotted in Figure 4, for a case later considered when the stabilization effect is calculated. For this case the ion sources emit between $\theta_1 = 12^\circ$ and $\theta_2 = 24^\circ$ and are located on a surface that is 2.5 meters from the mirror throat. The value of the scaling parameter, z_0 , in Equation 8 is 1.0 meter, the abscissa of the plot is axial position in meters and the ordinate is the ratio of the ion density at the given position to the ion density at the exit surface of the ion sources. Note that the convergence of the magnetic field flux surface plus the slowing and reflection of the injected ions results in a ion density peak at about 2 meters from the mirror throat with a peak value that is some 35 times larger than the average density at the ion sources.

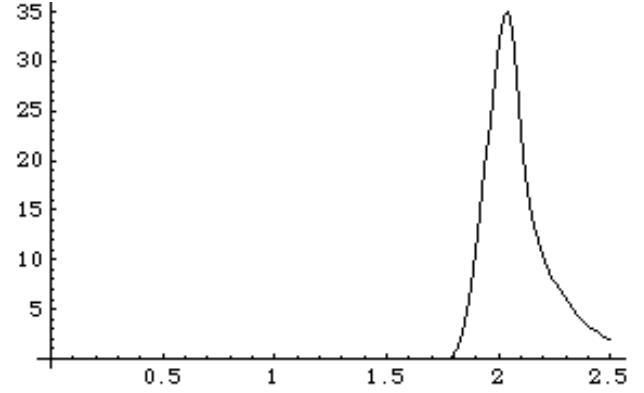


Figure 4: Kinetic Stabilizer relative ion density vs axial position (m.).

IV) CALCULATION OF THE MHD STABILITY INTEGRALS

To evaluate the conditions required to stabilize a plasma confined in an axially symmetric mirror cell by the Kinetic Stabilizer plasma it is first necessary to calculate the value of the stability integral, Equation 1, for the confined plasma. For the calculation of the quantitative requirements for stability the pressure of this plasma will be normalized to unity at the midplane of the system. In the examples to be considered the variation of the pressure between the midplane and the mirror will be assumed to be approximated by a eighth-order dependence in z , namely,

$$\frac{n(z)}{n(0)} = 1 - \left[\frac{z}{z_m} \right]^8 \quad (9)$$

The plasma density will also be assumed constant as a function of radius out to the bounding flux surface. For the examples to be considered later, the scale-length parameter, z_m , is taken to be 4.0 meters. Also, for the example here, a mirror ratio of 2:1 has been assumed, with the mirror cell magnetic flux function being represented in terms of Bessel Functions and having the following form:

$$\Psi = \pi B_{00} r^2 \left[1 - \frac{1}{3\pi} \left(\frac{L}{r} \right) \text{Cos}(u) I_1(\rho) \right] \quad (10)$$

Here $u = (2\pi z/L)$, $\rho = (2\pi r/L)$, and L is the scale-length of the mirror cell, with the mirrors being located at $z = \pm (L/2)$. Figure 5 is a plot of the bounding flux surface, $r(z)$, for a case where $L = 8$ meters and $r = .05$ m at the mirror throat ($z = L/2$).

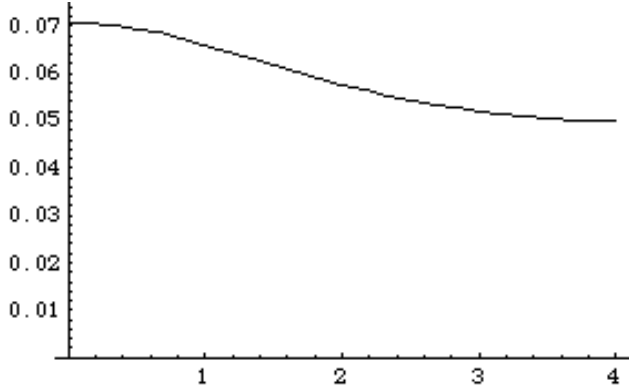


Figure 5: Flux surface function, $r(z)$, for mirror cell: (dimensions in meters)

To perform the stability integral of Equation 1 for this mirror-cell flux function, a plasma pressure equal to unity was assumed at $z = 0$ and the variation of plasma density given by equation 9 was assumed. In Equation 1 the pressure was assumed to be proportional to the density. The value of the integral obtained thus has been normalized for later comparison with the value of the integral obtained for the Kinetic Stabilizer plasma. With these assumptions the value of the integral, as evaluated between $z = 0$ and $z = L/2$, is found to be $I_M = -1.73043 \times 10^{-6}$, the negative sign corresponding to instability. To achieve stability it is then required that the corresponding integral for the Kinetic Stabilizer plasma, I_{KS} , should be a positive quantity that is larger than I_M . (assuming there are Stabilizer plasmas at each end of the system).

To calculate I_{KS} we employ the Gaussian-case flux function shown plotted in Figure 3. If we at first assume that a stabilizing plasma of unit pressure exists between $z = 1.9$ and 2.1 meters on that flux surface, we find for I_{KS} the value $I_{KS} = +0.39427$, corresponding to a stabilizing effect. Comparing this value with I_M we find that the ratio of their absolute values is 4.5×10^{-6} . We therefore find that the pressure of the stabilizer plasma can be more than five orders of magnitude smaller than that of the confined plasma and still stabilize it against MHD instabilities.

We have determined, as is plotted in Figure 4, the density peaking function as calculated by a transformation of variables from the integration of Equation 3. Thus we can now determine the ratio of the surface-averaged kinetic pressure at the exit surface of the ion sources (located at a distance of 2.5 meters from the mirror throat) to that of the pressure of the confined plasma, thus finding the Kinetic Stabilizer plasma pressure required to stabilize that plasma. When this

function was used as input in the code for evaluating the value of the integral for this source function, I_S . The value found is $I_S = 11.550$. Comparing this value with the absolute value of I_M we find $I_M/I_S = 1.5 \times 10^{-7}$. That is, in the present example the kinetic pressure of the stabilizing ion beams, as averaged over the surface on which the sources are located, can be nearly 7 orders of magnitude lower than that of the confined plasma and still satisfy the stabilization criterion, Equation 1. Of course, if the Kinetic Stabilizer plasma is produced by an array of ion sources covering only a portion of the area of the surface on which they are located, the ion density at the sources must be correspondingly higher. However, a simple estimate shows that the emission densities that would be required are well within present practice.

V) PATHS TOWARD OPTIMIZATION OF THE KINETIC STABILIZER

In the calculations that have been presented up to this point the field configuration of the expander region has been the one associated with a Gaussian decrease of the magnetic field with axial position. However, examination of the integral in the MHD stabilization criterion, Equation 1, suggests that there should be other expander field configurations that would give superior performance as compared to the Gaussian case. As an example an expander design was analyzed in which the flux surface resembled a trumpet horn, i.e. a conical expansion region (zero second derivative), followed by a short outward-curving region with a large positive second-derivative. It was found that when the Kinetic Stabilizer plasma was optimally located on the outward-curving section, the MHD stability integral, Equation 1, for this case was almost an order of magnitude larger than that for a Gaussian expander of comparable dimensions. Though a more detailed analysis would be required to confirm this result, it suggests that there should be ways to optimize the performance of Kinetic Stabilizers by paying close attention to the details of the magnetic field in the expander region.

VI) FUSION POWER BALANCE CONSIDERATIONS: A SIMPLE EXAMPLE

The calculations presented to this point suggest that it should be possible to MHD-stabilize a fusion-relevant plasma in an axially symmetric mirror system by maintaining a low-density plasma at a suitable location in the diverging field outside the mirrors. To assess the potential of the technique it is of value to estimate the power required to maintain the stabilizing plasma using the Kinetic Stabilizer approach and then to compare this power with the fusion power released. To present a simple example case we will make the following assumptions:

- The fusion plasma is contained in simple mirror geometry between two end mirrors. the flux surfaces of which are as shown in Figure 5, with a central region that is a long solenoidal field (makes no contribution to the instability integral, since the field line curvature here is zero).
- The magnetic field in the expander is the one associated with the Gaussian field variation, the results for which were described in Section IV.
- The central confining field is 5.0 Tesla, the radius of the plasma column at the mirror throats is .05 meters, and the mirror ratio is 2.0, so that the plasma radius in the central region is .0707 m.
- The fusion plasma is 50-50 DT with $T_i = T_e = 15$ keV and a total beta value of 0.3 (as demonstrated in the Gas Dynamic Trap).
- The Kinetic Stabilizer plasma is composed of low energy electrons and once-reflected 1.0 keV Cs^+ ions (easy to produce, and favorable because their higher mass reduces the beam power requirements).
- As in the example given in Section IV, the ion sources are located on a surface that is 2.5 meters distant from the mirror throat. At this location the value of B is approximately .02 Tesla (200 Gauss).

Given the above parameters, the calculated density of D and T ions in the central cell (assumed, for simplicity, uniform out to the plasma boundary) is $6.2 \times 10^{20} \text{ m}^{-3}$, resulting in a calculated fusion power release from the central cell (including the neutron-capture energy in a Lithium-containing blanket) of 1.6 Megawatts per meter. Thus, for example, the recovered fusion power from a 25 meter-long central cell (at an assumed 33 percent conversion efficiency) would be about 15 MWe. This power should now be compared with that required to maintain the Kinetic Stabilizer plasmas at each end.

As described in Section IV, the ratio of the plasma pressure (required for stabilization) at the surface on which the ion sources is located to the plasma pressure in the central cell is 1.5×10^{-7} . Since the sources are located on a surface that is 2.5 meters away from the mirror throats the ratio of the area of that surface to the area of the plasma cross-section at the mirror throat is approximately equal to $\exp[(2.5)^2] = 520$, so that the area of this surface is $\pi \times (.05)^2 \times (520) = 4.1 \text{ m}^2$

The sum of the kinetic pressures of the DT ions and the electrons in the central cell is $(6.2 \times 10^{20}) \times (2.) \times (15. \times 10^3) \times (1.6 \times 10^{-19}) = 3.0 \times 10^6 \text{ Pa}$. Thus for stabilization the average kinetic pressure of the Cs^+ ion

beams at the surface on which the sources are located must exceed $3.0 \times 10^6 \times 1.5 \times 10^{-7} = 0.45 \text{ Pa}$.

For estimating purposes we assume the kinetic-theory definition of the ion pressure at the ion source, i.e., as given by $p = (1/3)nMv^2$. With this assumption and from the velocity of a 1 keV Cs^+ ion ($3.8 \times 10^4 \text{ m/sec.}$) we deduce that the Cesium ion density, as averaged over this surface, is about $4.2 \times 10^{15} \text{ m}^{-3}$. This ion density then corresponds to an averaged current density of about $27. \text{ A/m}^2$, i.e., 2.7 mA/cm^2 . The ion-beam power is thus equal to $P_{\text{ion}} = (27.) \times (10^3) \times (4.1) = 110 \text{ kW}$, or a total power (both ends) of 220 kW. This amount of power is clearly much less than the fusion power output calculated for this example.

The example just given is not presented as a viable fusion power system, as it makes no provision for plugging the end leakage from its simple mirror system. It is given simply to show that MHD-stable fusion-relevant plasmas can be confined in axially symmetric mirror-based systems that are stabilized by Kinetic Stabilizers whose power requirements are small even as compared to the power output from a fusion power system generating less than 100 Megawatts of electricity.

VII) DISCUSSION AND CONCLUSIONS

The calculations presented in this paper have as their starting point an underlying thesis. This thesis is that in the search for magnetic fusion systems that are smaller, simpler, and more likely to be economically viable than present approaches such as the tokamak, those systems should be considered that, (1) theory and experiment have shown to permit the confinement of high-beta plasmas whose cross-field transport is not dominated by turbulent processes, (2) are simple enough in their magnetic field geometry so as to minimize the cost and complexity of their magnet coils, and (3) can be visualized to produce useful power at levels substantially below the Gigawatt level projected for approaches such as the tokamak or the stellarator.

While the thrust of this paper has been to describe a new and simpler configuration for tandem mirror fusion power systems, what has not been attempted in writing this paper is to present a design of such a system. Preliminary calculations, not presented here, suggest the possibility of reviving the first-suggested, simpler, form of the tandem mirror [7,8] as a viable fusion concept. Should this be the case it might overcome present concerns about the complexity of tandem mirror systems that are based on magnetic-well fields and that require thermal barriers for their operation.

Although in this paper there has not been a discussion of such issues as cross-field transport in the

proposed new configuration, the favorable experimental results of the Gas Dynamic Trap, where results consistent with classical transport were observed at beta values as high as 30 percent, taken together with the results of earlier axially symmetric mirror experiments, augur well for this issue. As noted earlier, the basic physics behind the Kinetic Stabilizer idea has been successfully demonstrated in the Gas Dynamic Trap. As to the theory undergirding the Kinetic Stabilizer idea, Ryutov [3] has discussed the constraints imposed by theory on the stabilization of axially symmetric systems by plasma located in the expander region. It is believed that these constraints can readily be satisfied in the design of Kinetic Stabilizers for full-scale fusion power systems. It should be possible to explore both of these issues (stabilization and radial transport) in small (University-scale) experiments. If these experiments prove successful it would then be time to propose the Kinetic Stabilizer configuration of tandem mirror as a serious contender for a fusion power system.

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